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Heading sensors remain the weak link in AUV navigation. Developers are left to chose between the size and expense of a gyro compass (and its variants) or the performance limitations of a magnetic reference. While the performance of a magnetic reference can be improved with a deviation table, implementing them is cumbersome and time consuming. A method has been developed for the REMUS vehicle that dynamically learns the compass errors using acoustic information as part of a regular mission. The approach is automatic, and applicable to any AUV operating in an acoustic net. This paper discusses test results, and future areas for development.

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DYNAMIC CALIBRATION OF A MAGNETIC HEADING SENSOR USING AN ACOUSTIC NET

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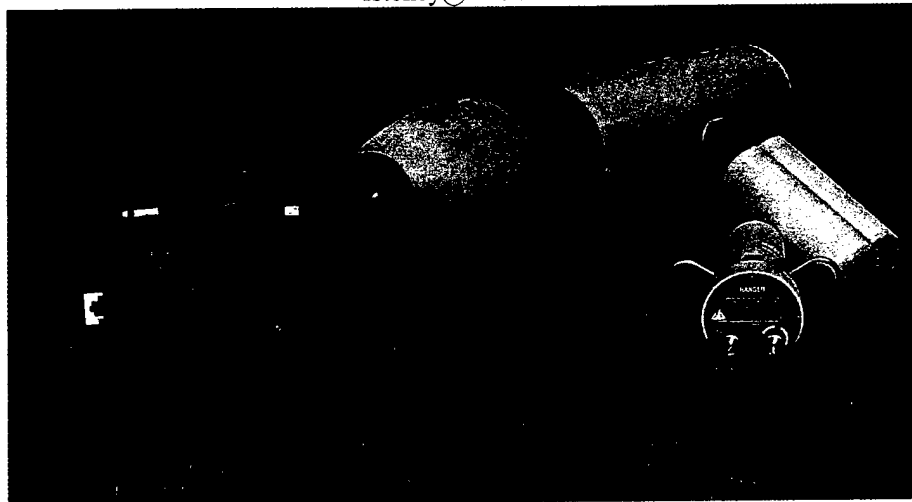**Woods Hole, Massachusetts**
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Fig. 1. Laptop, REMUS, GPS receiver, Ranger and Transponders

Abstract

Heading sensors remain the weak link in AUV navigation. Developers are left to chose between the size and expense of a gyro compass (and its variants) or the performance limitations of a magnetic reference. While the performance of a magnetic reference can be improved with a deviation table, implementing them is cumbersome and time consuming. A method has been developed for the REMUS vehicle that dynamically learns the compass errors using acoustic information as part of a regular mission. The approach is automatic, and applicable to any AUV operating in an acoustic net. This paper discusses test results, and future areas for development.

Introduction

The engineers and scientists that make up the AUV community on the whole are a fairly easy going group. When you're in the business of throwing equipment off the side of a ship and hoping it comes back, you learn to relax, get an ulcer, or go into some other line of work. None-the-less, through participation in a number of ONR AUV-Fests[1] and Navy fleet exercises with other AUV developers over the last several years, I have learned that late at night, bringing up the subject of heading sensors (and which approach is best!) can set off some pretty interesting discussions. Nobody lacks for opinions.

Only a fool would attempt to contribute something new to this debate. But then, only a fool would be in the business of throwing perfectly good equipment off the side of a ship and hoping it comes back.

About REMUS

REMUS[2,3,4] is a low cost, light weight, autonomous underwater vehicle designed to be operated using a Windows laptop computer. By making it low cost, it is accessible to as many users as possible. By making it light weight, launch and recovery are simplified, since special handling equipment is not required, and overnight shipping via commercial carrier is possible. At less than 80 pounds, a standard configuration carries an up and down looking RDI ADCP, Marine Sonics sidescan sonar, a CTD (YSI, FSI, and Ocean Sensors have all been integrated), and a Wetlabs light scattering sensor. Many other instruments have also been integrated, including a fluorometer, bioluminescense sensor, radiometer, acoustic modem, Sontek acoustic Doppler velocimeter, and Imagenex altimeter. Others are continually being added, including a plankton pump, a video plankton recorder, and an electronic still camera. It has successfully performed thousands of missions. Because it is so easy to use, a large number of non-technical people have been taught to operate the vehicle, including about 2 dozen Navy Seals. This simplicity is evident in terms of

ease of mission programming, operation, recovery, and data download and analysis. Routine maintenance consists of washing it down with a hose, and recharging the batteries, which does not require opening the housing, but merely plugging in a cable and pressing a button. As a result, it is an extremely reliable vehicle.

REMUS Heading Sensor

The single most critical technology in developing an autonomous underwater vehicle is its navigation system, and the most critical component within that system is the heading sensor. In general, AUV developers have used one of two methods. When size, cost, and power consumption are not a major concern, then a variant of the gyro compass is used, and by directly or indirectly measuring the earth's rotation, are able to determine the direction of true north. Specifications generally claim an accuracy better than 0.5 degrees.

When cost, size, or power consumption are an issue, then a magnetic reference is used. The accuracy of these systems are at best open to interpretation, however under controlled conditions, an accuracy of 0.5 degrees is also typically claimed. Unfortunately, in real world situations errors of several degrees with respect to true north are not uncommon for a variety of reasons: the magnetic environment of a small AUV is anything but benign and the accelerations that a vehicle undergoes in the near shore environment also degrade the heading reference. Even errors in the estimation of magnetic declination, the difference between magnetic and true north, can have a significant effect.

Unfortunately, the size and cost of a gyro compass are still incompatible with the requirements of a low cost, light weight vehicle. For this reason, REMUS development has concentrated on achieving the highest possible performance from a magnetic heading reference.

The REMUS heading sensor consists of a Precision Navigation Inc. (PNI) TCM-2 tri-axial fluxgate magnetometer, combined via a low-pass filter with the integrated and high-passed output of Systron Donner quartz rate sensor. The DC offset of the rate sensor is minimized by comparing the long term integrated output to that of the compass, and nulling out the residual component.

Normally, REMUS navigates using long baseline navigation using two or more transponders. Since this method is based solely on the range the vehicle is from the transponders, it is relatively immune to mi-

nor compass errors. Because the REMUS acoustic navigation system uses spread spectrum signals, it is extremely precise, and provides an accurate means for determining compass errors.

Magnetic Compass Errors

A simple model of compass error reduces it to three components. "Hard iron" errors are due to actual permanent magnetization of items near the compass itself. This results in minimal deviation when the heading is aligned with the magnetic field, and maximum deviation when the heading is perpendicular to the field, thus this error can be modeled is a sinusoidal component of unknown phase and amplitude (or as the sum of a sine and cosine components). DC currents in an AUV are an obvious source of hard iron errors, except that as currents vary so will the magnetic field generated.

"Soft iron" errors occur when magnetically permeable items near the compass cause a deflection of the magnetic lines of force in the vicinity of the compass. This results in a deviation that is zero at four equidistant points on the compass, and thus is a 2x sinusoidal component.

The third component can be viewed as a simple rotation, due to errors in alignment of the compass and vehicle frame, or due to errors in the estimation of declination.

Using this model of magnetic compass errors, an approximate deviation table can be constructed by measuring the error at 8 points on the compass, and then plugging those values into the following formula[5]:

Deviation at angle $\emptyset$ =
$A + B \sin(\emptyset) + C \cos(\emptyset) + D \sin(2\emptyset) + E \cos(2\emptyset)$

Where:

A=(d0+d45+d90+d135+d180+d225+d270+d315)/8.0
B=(d90-d270)/2.0
C=(d0-d180)/2.0
D=(d45-d135+d225-d315)/4.0
D=(d0-d90+d180-d270)/4.0

and d0, d45, etc. are the measured deviations at 0 degrees, 45 degrees, etc.

Unfortunately, this approach has its limits. To begin with, it does not generate an *exact* curve fit to the actual data (There are, in fact, other formulas that may be used). Furthermore, real world data doesn't always fit this simplistic model. For example, at a different pitch or roll angle than that for which the

calibration was performed, the deviations may be different. Shipboard magnetic compasses compensate for this by installing heeling magnets in the binnacle.

Calibration Approaches

A number of approaches have been used for compass calibration by REMUS since it was first designed. Initially, the compass was simply calibrated by putting it in its "calibrate" mode, and walking the vehicle through the steps necessary. The TCM-2 requires 2 slow (1 minute each) rotations while providing moderate pitch and roll activity. Normally this was done in an area believed to be free of magnetic anomalies. PNI maintains that their calibration algorithm will correct for hard iron, but not soft iron, errors[6]. As a result, this procedure by itself provides an incomplete calibration.

To deal with that, deviations were then measured by placing the vehicle on a wooden turntable, pointing the vehicle in the eight directions (0, 45, etc), and measuring the residual errors. These were plugged into the formula above and used to generate a deviation table to correct the compass at all points.

Experience and experimentation has shown the compass needs to be re-calibrated when moved to a new geographic location. On ship deployments, this requirement proved to be difficult to implement. Furthermore, the performance of this approach was less than satisfactory.

To improve performance (and to simplify operations) the vehicle was "taught" the necessary steps to perform an in-water compass calibration. The vehicle enables calibration, swims two circles, and then resumes normal operation. Even *without* a deviation table, the results of this approach were superior to those achieved with a land based "manual" calibration. During this stage of development the vehicle was also programmed to automatically compute the required declination using the world magnetic model. This eliminated problems from operators failing to enter the correct declination for an area.

Unfortunately, the in-water calibration method provided no easy method to compute a deviation table. There was a continued desire, and clearly a need, to be able to construct such a table with the same simplicity that in water compass calibration provided.

Typical Problems

At first glance, a vehicle operating in an acoustic net doesn't need an extremely accurate heading reference. The near continuous acoustic fixes keep the vehicle from wandering too far off course. Unfortunately, the

reality is far more complex. A variety of situations can make it difficult or impossible to get acoustic fixes. For example, during operations at Ft. Lauderdale in June of 2000, REMUS was tasked to sidescan survey an area over a reef. The navigation transponders were placed off shore. During the survey, once the vehicle moved inshore of the reef it had a difficult time hearing the transponders, and was frequently required to dead reckon until it was back outside. Fig. 2 shows a bathymetry profile collected by REMUS of one of these transects. Since the vehicle was flying at a fixed altitude off the bottom, in the near shore region it was in the acoustic shadow of the reef.
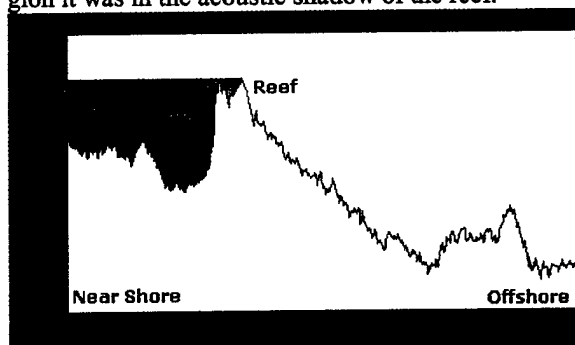

Fig. 2. Bathymetry Profile at Ft Lauderdale

Another situation where an acoustic net could be useful is in using an initial calibration so as to enable longer dead reckon runs. For example, at the LEO-15[7] site off of Tuckerton, NJ, the vehicle has routinely been launched from the outer node 5 kilometers offshore, navigated to a point 25 kilometers offshore, and then returned. During these missions, the vehicle both navigated and was tracked from shore using 6 PARADIGM[8] buoys placed a 4 kilometer increments. Accurate calibration of the compass at the beginning of the mission would allow long dead reckon segments, requiring fewer buoys and thus allowing longer transects.

Algorithm

The initial goal was very simple: the effortless construction of a deviation table, and if possible estimation of the five coefficients. A number of approaches were examined but all were rejected as too cumbersome or lacking in accuracy. One idea considered was to actually run 8 legs at 45 degree increments, measure the error, and use the errors to create a deviation table. However, this would require running a special mission for compass calibration every time the vehicle was moved to a new locale. Even then, there would be residual errors not corrected.

Also rejected was attempting to estimate the curve based on the few headings of a typical mission, which might have only have a transit leg to the sur-

vey area, then back and forth legs during the survey. It was felt estimating the coefficients from such a sparse data set might result in errors that were worse than if no corrections were made at all. Ultimately, efforts to estimate the 5 coefficients were abandoned.

None-the-less, it was clear that trying to calculate and apply a correction for each of the 360 degrees of the compass (or 3600 if you choose to look at decimal degrees) created an unwieldy problem.

A simpler, and thus more practical, solution presented itself. Rather than try to determine a correction based on the compass, generate a correction based on the direction of the leg the vehicle is on, and maintain a table of corrections for each leg direction. If, for example, the vehicle was navigating a box with legs of 0, 90, 180, and 270 degrees, maintain a table with a different correction for 0, 90, 180, and 270. If legs in a different direction are added, make additional entries into the table. This approach makes both the derivation and utilization of the table of corrections manageable.

The resulting algorithm is quite simple. REMUS continually maintains and updates its actual latitude and longitude position based on a fusion of acoustic and dead reckon data. It also maintains a purely dead reckon position based solely on compass and velocity.

Once the vehicle has settled in on a new course, the vehicle uses acoustic fixes that are at least 100 meters apart and calculates the precise range and bearing traveled. A similar calculation is performed with the raw dead reckon data from the same time period. The difference between the two bearings is assumed to be due to compass deviation, and is applied to a filter, that attempts to null out the difference by generating a correction for that leg. This approach for measuring error is fairly routine, but is most often implemented using GPS[9], and is used to generate the data for construction of a deviation table, or to estimate a single value of compass bias after constructing such a table.

Error Sources

Clearly this approach is a compromise. During a transit down a particular leg, the vehicle may yaw back and forth about the desired heading. The actual deviations for those off axis headings will be slightly different, but over short distances the effect will be miniscule, and over longer distances, average out.

If there is a significant current that results in the vehicle crabbing along a trackline, the deviation that is computed will be for a vehicle heading that is different from the actual leg heading. This does not matter. A sudden change in current may result in a sudden change in average vehicle heading, however the change in deviation will most likely be small, and the filter will quickly readjust.

An ADCP helps with the actual bottom velocity estimation, but it is not necessary. The approach has been used successfully with older REMUS vehicles that have neither the ADCP for measuring velocity over the bottom nor the rate sensor for improving compass performance under dynamic conditions.

One of the most significant sources of errors is differences between the actual and programmed transponder positions. Even using differential GPS, it is difficult to place the transponders closer than 5 or 10 meters to the desired position. A 8.75 meter rotational error in placing a transponder on a 1000 meter baseline will result in a half degree rotation of the entire field. A more common error is to place the transponders closer or further apart than expected. This results in the appearance that the "deviation" is changing at different points in the field on the same heading. This is actually a reliable metric of how accurately the transponders are placed. If the measured errors are consistent on a given heading throughout the field, then the transponders are reasonable accurately positioned.

Other errors occur because of errors in the estimation of sound speed.

Because there is no apriori knowledge of compass error (unless a particular direction has been run), it does not solve certain types of problems. In the Fort Lauderdale example cited, the vehicle will learn the correction needed for the inbound leg before passing over the reef, but on the first outbound leg, there will be no data. Once the vehicle moves outside the reef it will be able to learn the correction, so on the 2nd and subsequent outbound legs, it will have adequate knowledge to accurately dead reckon through the acoustic dead zone.

Results

Fig. 3. Bearing error for typical survey mission

A typical REMUS survey mission consists of launching the vehicle from one of two transponders that are deployed, having the vehicle transit to the survey area, mow the lawn over the survey area, and then return. The vehicle spends the majority of its time going back and forth. Because different deviations are calculated for each leg, the individual calculations when plotted resemble a square wave. What is apparent is that the errors are fairly consistent from leg to leg. Fig. 3 shows 8 legs of one such mission. In one direction the errors are around 3.9 degrees, in the other about -5.2 degrees. The standard deviation of the measurements for these legs are 0.69 and 0.71 degrees respectively.

A more complex test was performed in July of 2001 in Buzzards Bay. For this test the vehicle was programmed to run a series of 500 meter legs at 22.5 degree increments. The legs at 45 degree increments were used to construct a standard deviation table, and the legs in between were used to measure the error at those points. Fig. 4 shows how this mission was programmed, with the vehicle starting from and returning to the northern most transponder. The baseline was 700 meters long, with the center point 600 meters from that baseline.
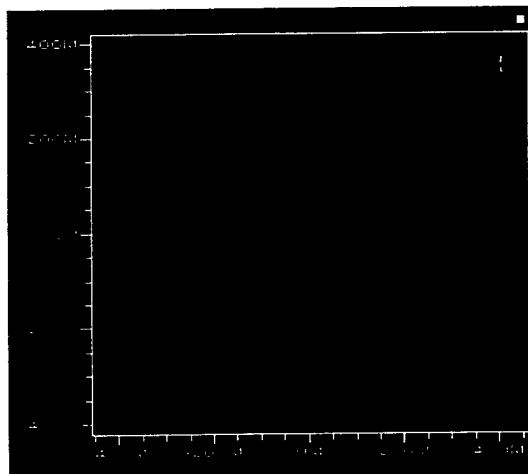

Fig. 4. Mission programmed for analyzing compass deviations

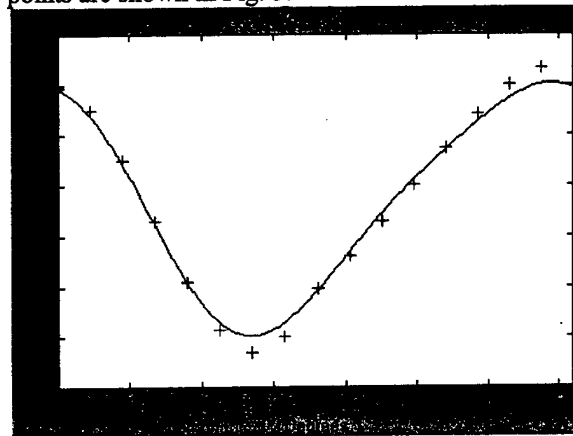The resulting deviation table, and the intermediate points are shown in Fig. 5.

Fig. 5. Plot of compass deviations, calculated and actual

While it is clear there is a pretty good fit between the actual data points and the deviation table constructed from these points, there are still residual errors, and not just on the intermediate points. Table 1 shows the data in tabular form. The mean is the average of the raw bearing error measurements for a given leg. "Std Dev" the standard deviation of those measurements. The "filtered" output is the deviation correction in use by the end of the leg. The "calculated" value is the result from plugging the filtered values from 0, 45, 90, etc. into the deviation formula. Delta is the difference between the filtered and calculated outputs, i.e. the residual error.

Degrees	Mean	Std Dev	Filter	Calc.	Delta

Table 1. Compass error data

It is interesting to note that the standard deviation is largest for those legs that are perpendicular or near perpendicular to the transponder baseline. This is expected, as errors in transponder placement would have their largest affect on these legs.

The mean of the residual error (Delta) is zero. This is not surprising, since the A coefficient is the mean of all the errors, and the remaining sine and cosine terms of course have zero average. What this means is that when using this formula for a deviation table, attempts to treat residual compass error as a simple rotation or bias will fail, since although there *are* residual errors, their average is zero. None-the-less, the technique will be successful while the vehicle maintains a single heading.

The coefficients derived from this table are as follows:

Coeff	Value	Effect

Table 2. Coefficients developed from data

It is interesting to note that the B and C coefficients, those that deal with the hard iron compensation, are significantly larger than the D and E coefficients. The PNI compass compensation algorithm is supposed to deal with the hard iron compensation.

When Things Go Wrong

Fig. 6. Calculated deviations with transponder adrift

The world is an imperfect place. Humans make mistakes; equipment breaks[10]. During one mission during Kernel Blitz in March of '01 at Camp Pendleton a shackle attaching an anchor to one of the transponders came loose, and the transponder and buoy started to drift. The vehicle continued to navigate as if the transponder were in its original location, however as transponder drifted further, the discrepancy between what the acoustics were indicating and the dead reckon information became larger. Fig. 6 shows the vehicle's estimation of the compass error as the vehicle conducted its survey, quite different from the usual square wave pattern seen such as in Fig. 3.

Fig. 7. Misplaced transponder errors
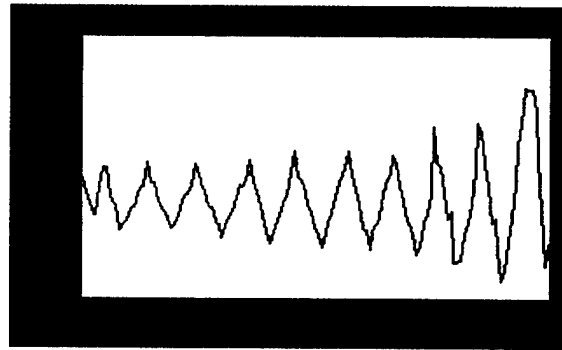
A different situation occurred during Navy Seal training. In that instance, a transponder placed in the wrong locale resulted in a similar pattern. Currently this information is merely providing post mission feedback as to the quality of transponder placement. In the future this information may allow enhanced estimation of the actual relative positions of the navigational transponders.

Conclusions

The calibration system in use by REMUS has proven to be extremely accurate in the challenging shallow water environment that REMUS usually operates. It allows short term dropouts of acoustic navigation to be reliably managed. It appears to reduce residual error to nearly half degree or less, and is totally transparent to the vehicle operator, since it does not require a special calibration mission.

Acknowledgements

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